LOW-VOLTAGE, HIGH-CURRENT-DENSITY ELECTRON BEAM SOURCES

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Electron beams are attractive for materials processing applications because of the potential for low-cost, compact sources. Electron range considerations dictate sources that are much lower in voltage, but with correspondingly higher current density, than comparable ion beam sources. The lower voltage has many advantages but requires an orders-of-magnitude enhancement of current density over that achievable with simple space-charge-limited vacuum gaps. Therefore, any electron beam source that does not rely on high geometrical focusing will need a plasma fill to supply the positive space charge necessary to exceed the space charge limited current. In addition, any source will require both a cathode capable of emitting high current densities at low voltages, and a means of guiding the beam to the target.

In the past we have studied plasma-filled diodes at the 100 kV-1 MV level for x-ray production and improved load coupling. We are now beginning to study plasma filled diode operation at low voltages to produce electron beams for materials applications. This paper presents our first work in this area.

Appropriate electron-beam sources require a low-voltage cathode, plasma to neutralize the beam space charge, and a means of guiding the beam to the target. Candidate cathodes include surface flashover sources, highly-enhanced structures like graphite fibers, and hollow cathodes. Plasma can be produced by a variety of surface-discharge sources, or by ionization of a gas ambient, either by the electron beam precursor or an auxiliary Penning discharge. The beam can be guided either magnetically or electrostatically by a dielectric channel.

Two existing, relevant sources are the channel spark, developed by Schultheiss and co-workers at the Karlsruhe Research Center [FZK] [1] (hollow cathode/beam-ionization in gas/dielectric guide) and the plasma filled diode source developed by Proskurovskii and co-workers at the Tomsk Institute of High Current Electronics [2] (graphite cathode/Penning discharge in gas/magnetic guide).

We began using the FZK channel spark source. After examining different variations, we replaced the hollow cathode with a surface-flashover cathode of rigid coax (left side of Fig. 1). This gave essentially the same voltage, current, and x-ray waveforms as the usual design but was slightly more compact and gave improved triggering reliability. This source was used in preliminary thin-film ablative deposition experiments.

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Substrates included Mn-Zn ferrite, YBCO, and LCMO (a material of interest because of its colossal magnetoresistance.) Beam parameters were 17-20 kV, 1-2 kA, 50-100 ns, and 10's J/cm^2, typical of prior channel-spark experiments. Results of these experiments led us to attempt to obtain electron beams of lower voltage (~10 kV) at the same energy density, to more closely match laser deposition profiles.

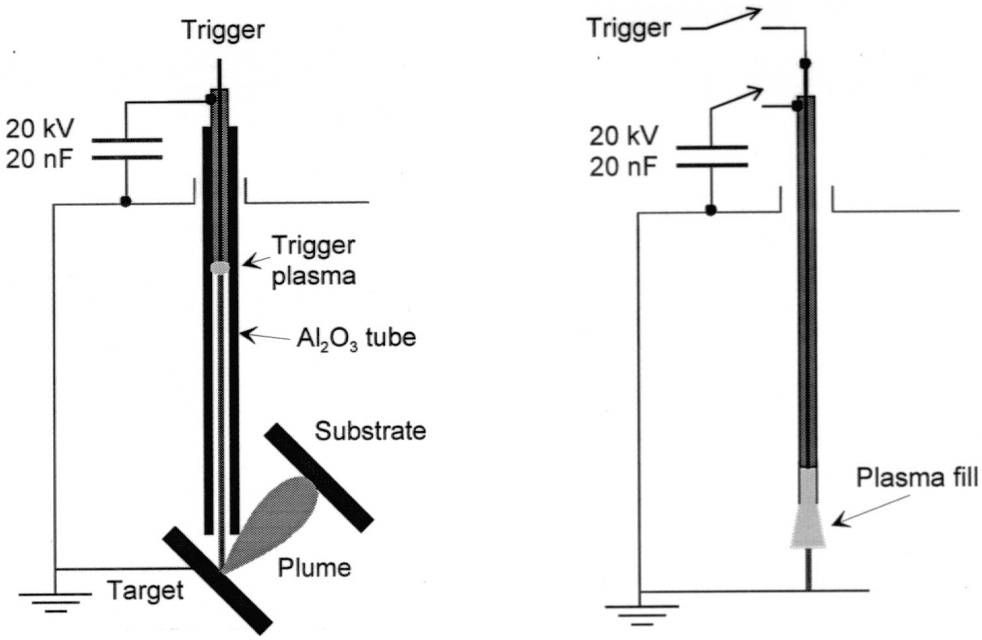

Fig. 1: Arrangement used in channel-spark deposition experiments (left) and in initial plasma-filled diode experiments (right).

We next studied at a plasma-filled diode configured like a 'traditional' plasma opening switch (right side of Fig. 1). The coax was brought closer to the target in a vacuum ambient. The trigger pulse supplied the necessary plasma, and after a few microseconds the main pulse was applied. The resulting impedance behavior was erratic and irreproducible, with many 'openings' and 'reclosings'. We attribute this to variations in supply of plasma from the source on the timescale of the main pulse. Because of this, and because of the ultimate possibility of workpiece contamination by cable material, we abandoned this approach. We are now focusing on sources where the plasma is produced by breakdown of the ambient gas.

Rather than using a Penning discharge as in the Tomsk experiments (and in previous plasma filled diode work at NRL [3]), we use a precursor to the main electron beam to ionize the ambient gas. This is potentially attractive because no auxiliary electrode structures are needed and transverse access (necessary, for example, for ablative deposition) is improved. This concept is tested using the small experiment shown in Fig. 2. The 3-mm diam carbon fiber brush cathode turns on at voltages of about 5 kV under the right conditions. The prepulse circuit charges the ~1-nF capacitance of the main bank cables to about 7 kV, at which time the precursor electron beam discharge occurs. Several microseconds later the main bank is triggered. Diode gaps from 2-4

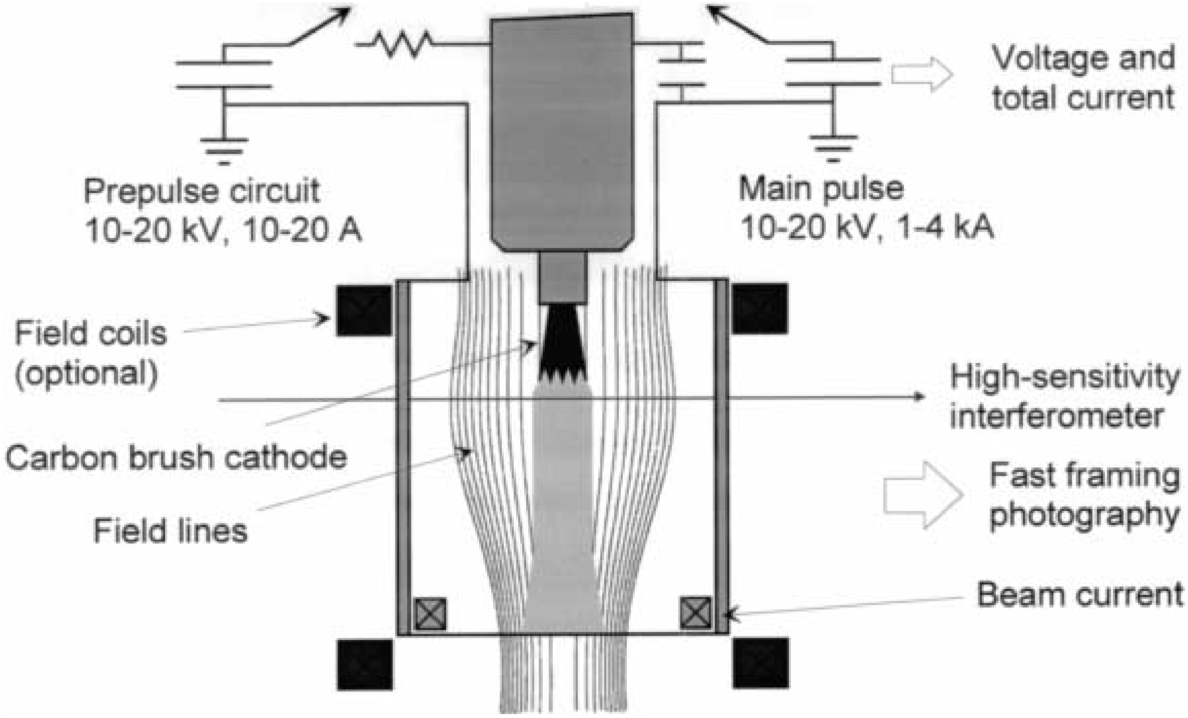

Fig. 2: Schematic of the experimental arrangement.

cm and background pressures from 0.5-5 mTorr have been used. The resulting beam is confined by a magnetic field that ranges from 0.7-1 kG at the cathode to 2.5 kG at the target. This plasma filled diode is diagnosed using standard electrical monitors, framing photography, and a highly sensitive interferometer.

If either the prepulse or magnetic field are absent, or if the carbon brush is replaced by a smooth surface, then the beam current is small or zero until a parasitic breakdown occurs in the feed. (It is likely that preionization is helped by the effect on the electron orbits of the radial component of the electric field at the cathode crossed with the axial magnetic field.) Under normal conditions, the impedance increases quickly from near zero to the operating impedance, and then drops to zero over 100-400 ns. The operating impedance scales as expected: decreasing as the pressure, main pulse delay, or prepulse voltage are increased. This scaling allows a range of beam impedances to be obtained. Waveforms for relatively high and low impedance shots are shown in Fig. 3. Most data were taken using air; a few shots taken with argon showed no dramatic difference. The rate of impedance collapse decreases as the impedance is increased. It is possible that the microsecond-range pulselengths obtained at Tomsk would also be obtained here if this source were operated at similar current density, but parasitic breakdown in this arrangement (which is not fundamental to this type of source) limited such measurements. The peak beam energies obtained at different impedances are 4-5 J, or about 50% of the initial stored energy.

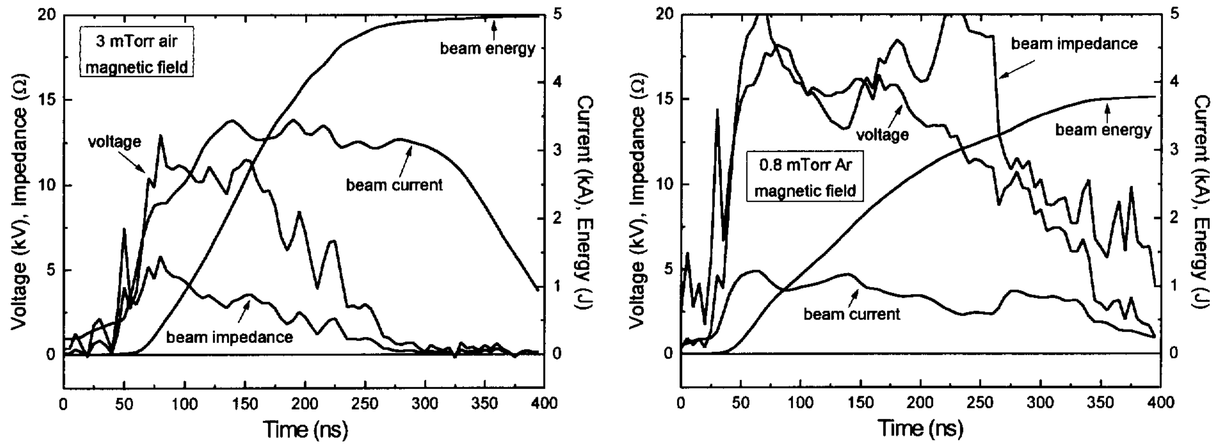

Fig. 3: Electrical waveforms for 2 ambient pressures, showing the range of obtainable impedance behavior.

Evolution of the plasma density in the diode is diagnosed using a highly-sensitive optical interferometer [4]. By combining a differential-detection scheme with multiple-timescale vibration isolation, sensitivities below 10^{-4} fringes are obtained. In this experiment a 1.06μ laser was used and the sensitivity to electrons is about $10^{13}/cm^2$ (line density). Typical data are shown in Fig. 4.

The prepulse is seen to produce a density that is relatively uniform axially and constant in time, corresponding to a high fractional ionization of the gas. Impedance collapse is correlated with an apparent motion of high-density plasma from the cathode. (This may be coincidental, however, since an increase in pulselength is not seen when the gap is increased.) Measurements obtained with the probe beam displaced radially indicate that the electron beam is between 0.5 and 1 cm in diameter. This is consistent with the observed damage patterns on the anode that are about 8 mm in diameter, and indicates peak energy densities of ~10 J/cm^2.

Intensified framing camera images are shown in Fig. 5. These shots were taken with 1 mTorr of air and a 5 microsecond pulse delay. During the prepulse a relatively uniform channel of light is seen whose shape is consistent with the applied field lines. When the main pulse arrives very bright light is seen at the cathode, and light is seen out in the gap as the pulse progresses. After the pulse a bright spot of light is seen at the target. The width of the prepulse luminous region is consistent with the 5-10 mm diam inferred from the density measurements and the ~8 mm diam seen on damage patterns.

The low-voltage (~10 kV), high current electron beams obtainable with magnetic field guiding at higher pressures are attractive for ablative deposition, but the energy density so far of 10 J/cm^2 is marginal for this purpose. The channel width is on the order of the electron Larmor radius, and by using a stronger applied field we may be able to decrease the beam size and thus boost the energy density. The beam parameters here are already attractive for direct materials modification, but for this we must scale the area up by 2-3 orders of magnitude. Our immediate plans are to build a 10's-cm^2 version of this source to investigate scaling issues. One advantage of a larger source is that the longer path length will improve the sensitivity of interferometric measurements. Finally, we plan to apply all of the theoretical tools we have used in studying higher-voltage plasma filled diodes to this problem.

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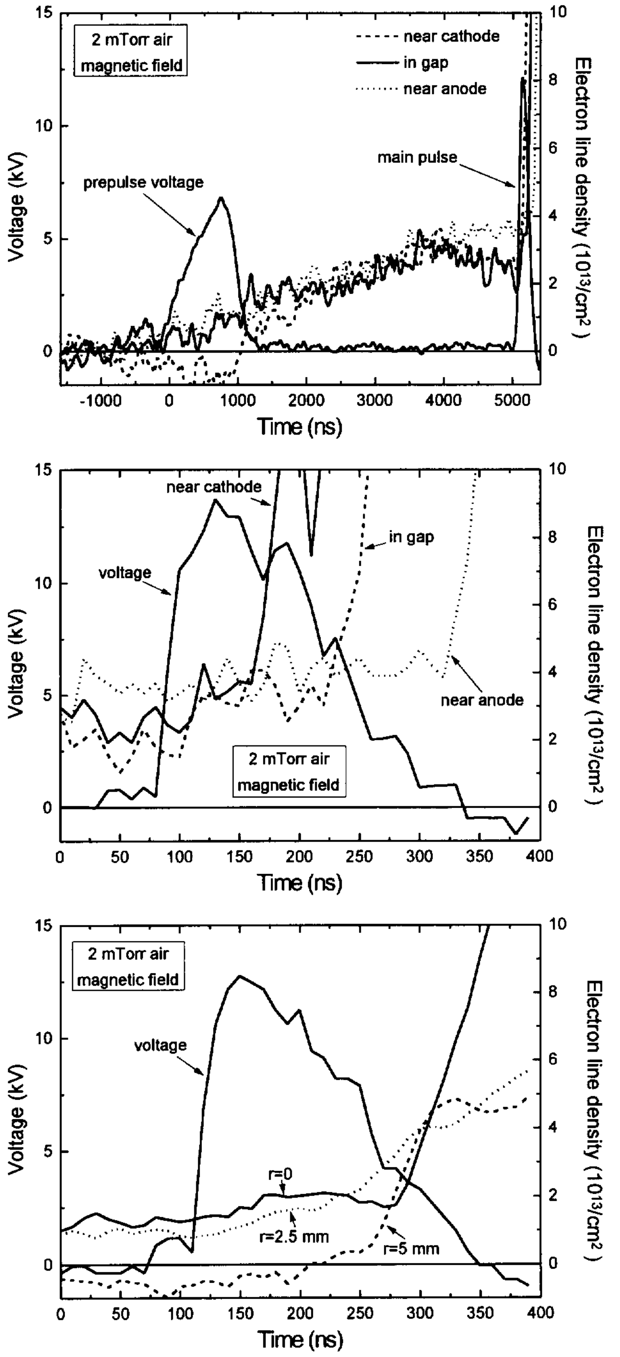

Fig. 4:
Electron densities obtained from interferometry at different axial locations during the prepulse (top), during the main pulse (middle), and at different radial locations during the main pulse (bottom).

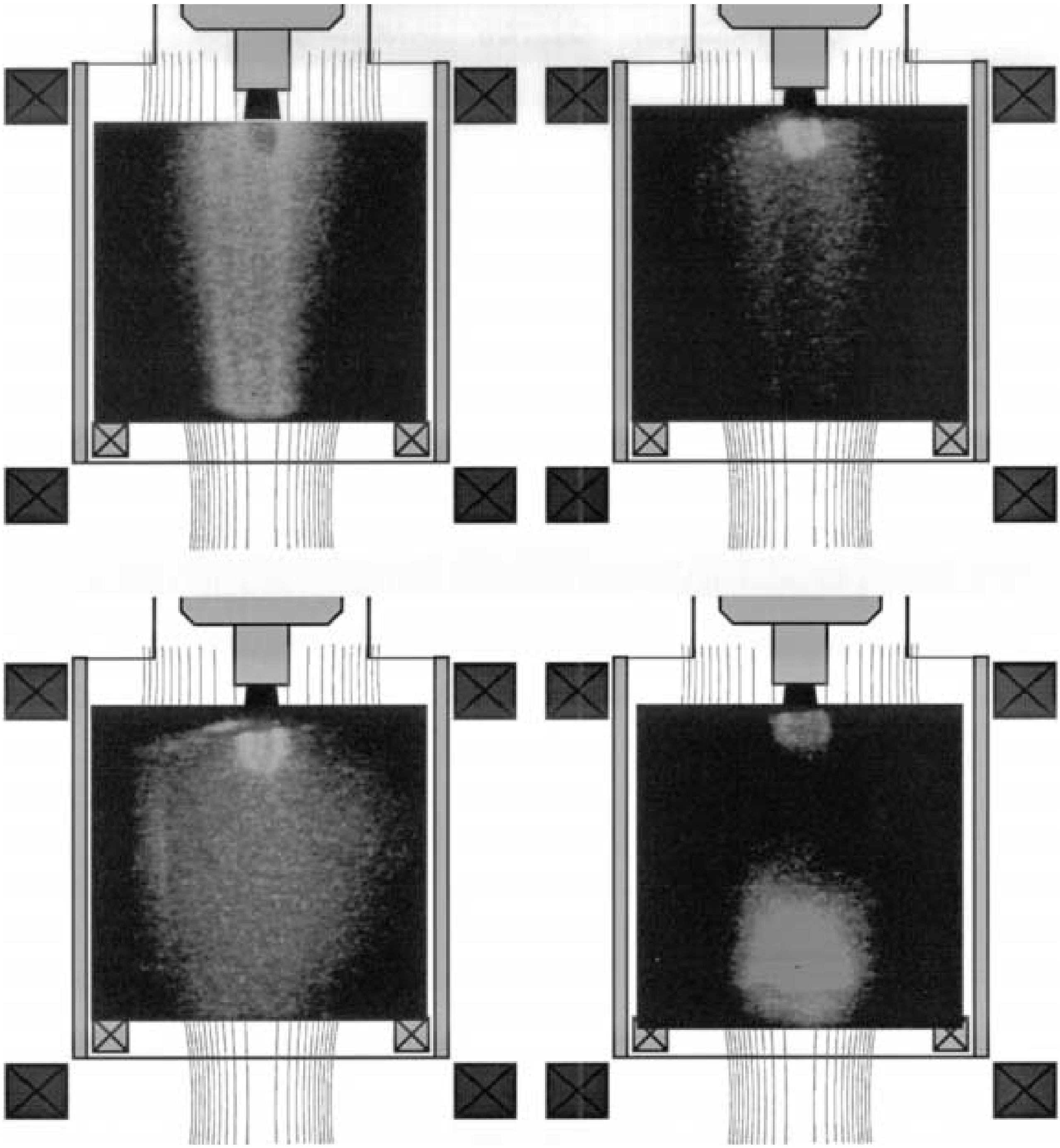

Fig 5: Framing photographs of the source: (top left) a 1-microsecond gate, taken during the prepulse. The relative optical attenuation is 1; (top right) the first 30 ns of the main pulse, with a relative optical attenuation of 10; (bottom left) the first 100 ns of the main pulse, with a relative optical attenuation of 240; (bottom right) a 1-microsecond gate, taken after the main pulse, with a relative optical attenuation of 240.